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CHARACTERIZATION OF OBSCURING SMOKES IN THE FIELD (U)

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INTRODUCTION: Objective characterization of conventional smokes and other obscurants in the field has become a matter of intense interest during recent years, paralleling the need for evaluating both new smoke munitions and the effectiveness of obscurants in degrading the performance of electro-optical systems and vision. Determination of physical, optical and visual properties of an obscuring cloud involves integrated assessments of the delivery system, of the target, target area, sky and sun or moon, of the cloud itself, and, in some instances, the response of observers. It requires suitable test areas and grids, detailed meteorological and photographic data capabilities, laboratories for chemical analyses and calibration, and systems for automatic acquisition and reduction of the staggering volume of data resulting even from field trials of modest proportions. Dugway Proving Ground has established a stand-alone system for testing of obscurants in the space of about one year, employing in-house developments in instrumentation and methodology which culminated in eminently successful programs conducted during 1977 for the Program Manager, Smoke/Obscurants. Each of the relevant aspects mentioned above could easily serve as the subject of a separate paper. The present report, however, will be limited to a description of certain mathematical procedures, a schematic representation of a section of the test grid with location of instruments and targets to aid in interpretation of the procedures, and presentation of representative test results. (Figures 2-9 and Table 1)

MATHEMATICAL PROCEDURES+: Atmospheric particulates may be regarded as constituting a more or less dilute cloud which extends over the

+For explanation of instrument locations, see Figure 1.

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entire distance between transmitters or targets to the receivers. This atmospheric haze, like clouds of obscurants, exhibits luminance and attenuates electromagnetic radiation. Although frequently negligible, corrections for these effects and for changing light conditions are routinely applied, using the first three procedures.

Transmittance of the Atmosphere (T_A). The transmittance (T_A) of the atmosphere over the line of observation is obtained using

$$T_A = \frac{R_{02} - R_{01}}{R_{03}} \qquad (\lambda = 0.4\text{-}0.7\ \mu m) \tag{1}$$

where R_{01} = average reading of telephotometer No. 1 (Figure 1) when observing the non-reflecting black target located at position (2) prior to arrival of smoke cloud, footlamberts.

R_{02} = average reading of telephotometer No. 1 (Figure 1) observing the white target located at position (2) prior to arrival of smoke cloud, footlamberts.

R_{03} = average reading of telephotometer No. 1 (Figure 1) when observing the white target located at position (8) prior to arrival of smoke cloud, footlamberts.

Luminance of Atmosphere (L_A). The luminance (L_A) of the haze is determined by

$$L_A = R_{01} \qquad (\lambda = 0.4\text{-}0.7\ \mu m) \qquad \text{(see Table 1)} \tag{2}$$

Correction Factor (C_f). The observations recorded by telephotometer No. 1 (Figure 1) are corrected by the factor (C_f) to normalize all the readings to the light conditions which existed at the beginning of the test. The correction factor is given by

$$C_f = R_{03}/R_3 \qquad (\lambda = 0.4\text{-}0.7\ \mu m) \tag{3}$$

where R_3 = reading of telephotometer No. 1 (Figure 1) when observing the white target located at position (8) as a function of time, footlamberts.

Luminance of Smoke Cloud (L_c). Cloud luminance (L_c) is given by

$$L_c = C_f R_1 - R_{01} \qquad (\lambda = 0.4\text{-}0.7\ \mu m) \qquad \text{(see Figure 2)} \tag{4}$$

where R_1 = reading of telephotometer No. 1 (Figure 1) when observing the black target located at position (2) as a function of time, footlamberts. Equation (4) assumes L_A is small compared to R_1. Analogous measurements were also made at 1.06 μm, and cloud radiance was determined at longer wavelengths.

Reflectivity of Target (r_t). The reflectivity (r_t) of the target is given by

$$r_t = \frac{R_{05} - R_{01}}{R_{03}} \quad \text{(see Table 1)} \qquad (5)$$

where R_{05} = average reading of telephotometer No. 1 (Figure 1) when observing OD target located at position (2) prior to arrival of the smoke cloud, footlamberts.

Luminance of Any Target (L_t). The luminance of any target can be obtained if the reflectivity (r_t) of the given target is known using

$$L_t = r_t \cdot R_{03} \quad \text{(see Table 1)} \qquad (6)$$

Transmittance of Cloud (T_λ). The transmittance at any given wavelength (λ) is given by

$$T_\lambda = \frac{R_{on} - R_{off}}{\overline{R}_{on} - \overline{R}_{off}} \quad \text{(see Figure 3)} \qquad (7)$$

where R_{on} = reading of the receiver observing a chopped light source of wavelength λ, light "on", units

R_{off} = reading of the receiver observing a chopped light source of wavelength λ, light "off", units

$\overline{R}_{on}$ = average value of R_{on} before the smoke cloud arrives, units

$\overline{R}_{off}$ = average value of R_{off} before the smoke cloud arrives, units

Transmittance measurements were obtained as follows:

Lines 1 & 3: λ = 3.4 μm

Line 2: λ = 8-12, 0.4-0.7, 1.06 and 3.39 μm

Slant range: λ = 1.06 μm

Aerosol Sampling. a. Aerosol photometer. Analog data from APs were digitized and recorded on magnetic tape. In this form, the data were in terms of relative concentration through time. The relative concentrations were converted to "true" concentrations (mg $H_3PO_4 \cdot nH_2O/m^3$ or $ZnCL_2 \cdot nH_2O/m^3$) utilizing ADP software and data from chemical impingers located at the instrument site, i.e., they were individually field calibrated in each trial. Concentrations at one-second intervals were tabulated for each AP position. Plots of the time-concentration relationships at each AP position and CL (concentration-length product) values as function of time were prepared where CL is defined by

$$CL(t) = \int_0^L C(t)dL \qquad \text{(see Figure 4)} \qquad (8)$$

where C(t) = concentration along the line of sight at a given time (t) (see Figure 5), and

L = distance along the line of sight, meters

Equation (8) was numerically integrated to obtain the CL values.

b. Chemical Impinger. The impingers were assayed according to the DPG SOPs for phosphorus or zinc. Assay results were converted to a dosage (mg $H_3PO_4 \cdot nH_2O$ or $ZnCL_2 \cdot nH_2O$ min/m^3) for each trial.

c. Particle Size Analyzer. Analog PSA data were digitized and stored on magnetic tape. The magnetic tape was processed by ADP. These procedures provided, at a given time of cloud history, PSA-derived concentration (particles/m^3), particle size distribution as a proportion from each channel of the PSA to the total number of particles counted across all six channels, log NMD (number median diameter) as determined by probit analysis, probit slope, variance estimates to log NMD and probit slope, NMD and MMD (mass median diameter) for each trial and smoke submunition.

CL Values. CL has been defined above and can also be determined from the Beer-Lambert law CL = $\ln T_\lambda / -\alpha$ (9) (see Figure 4),

where α = extinction coefficient (m^2/g) and can be determined from field data (transmittance and impinger dosage) as seen in the following paragraph, and where T_λ = transmittance at a given wavelength λ

The CL values obtained using equation (9) were obtained for all lines of sight as a function of time.

CL Values of Two-Component Systems. When dealing with two-component systems, e.g., smoke and dust, determination of CL(t) might appear impossible since the CL values for the components may vary independently of each other as well as with time. However, when the extinction coefficients differ significantly at selected wavelengths (as they do in the case of smoke and dust), CL(t) values can, in fact, be evaluated: Let $d = \alpha(CL)$, so that at two different wavelengths at the same instant for component 1 $d_1 = \alpha_1(CL)_1$ and $d_1' = \alpha_1'(CL)_1$ and, similarly, for component 2 $d_2 = \alpha_2(CL)_2$ and $d_2' = \alpha_2'(CL)_2$. The actual measurements made are $d_1 + d_2 = D$ and $d_1' + d_2' = D'$, respectively. The relationship of $(CL)_1$ and $(CL)_2$ is fixed, and can be established if the extinction coefficients are predetermined. Consider that $D = \alpha_1(CL)_1 + \alpha_2(CL)_2$ and $D' = \alpha_1'(CL)_1 + \alpha_2'(CL)_2$. Since, by rearrangement, $(CL)_2 = (D' - \alpha_1'(CL)_1)/\alpha_2'$, by substitution, $(CL)_1 = (\alpha_2'D - \alpha_2D')/(\alpha_1\alpha_2' - \alpha_2\alpha_1')$, which is of the form $(CL)_1 = \omega D - xD'$, or $x\ell nT' - \omega\ell nT$. Using values of $(CL)_1(t)$, one may then solve for $(CL)_2 = D'\{(1 + \alpha_1'x)/\alpha_2'\} - (\alpha_1'\omega D)/\alpha_2')$, which may be represented by $(CL)_2 = yD' - zD$ or $z\ln T - y\ln T'$, where T is the transmittance. Thus, CL(t) for each of the two components in the cloud can be established regardless of dynamic changes in composition of the cloud. Indeed, it is not essential that the two components actually be mixed along the line of sight. Necessary conditions are that the Beer-Lambert law be obeyed for each component, and that the two components do not interact.

Photometric Contrast Ratio. The photometric contrast ratio is defined by $C_t = T(L_T - L_B)/(TL_B + L_C)$ (10).

where T = transmittance in the visual (λ - 0.4-0.7 μm)

L_t = luminance of the target, footlamberts

L_B = luminance at the background, footlamberts

L_c = luminance of the cloud, footlamberts

The reflectance is determined by r = luminance of object/luminance of white target (11). Equation (10) can then be written $C_t = R_{03}T(r_T - r_B)/R_{03}Tr_B + L_C)$ (12).

where R_{03} = luminance of a white target (provided by the tests), footlamberts where T = transmittance (λ = 0.4-0.7 μm) (provided by the tests)

L_c = luminance of the cloud (provided by the tests)

r_T = reflectance of any target

r_B = reflectance of any background. The luminance of the background was measured by using telephotometer No. 1 (Figure 1) and the background in the field of view along line of sight No. 2 and r_B was determined using equation (11).

The significance of this approach is that the contrast ratio of any desired (actual or hypothetical) target can be computed without the need of physically locating such a target in the test area, provided only that the reflectance of the target is determined, which is simple. Thus, costs, time and effort are saved, without limitation on extent of data acquisition.

Calculated Transmittance. When the readings at a given wavelength (λ_1) approached the noise level of the recorders, the transmittance at these wavelengths was calculated using the following equation:

$$T(\lambda_1) = T(\lambda_2)^K \quad \text{(see Figure 6)} \tag{13}$$

where $T(\lambda_1)$ = transmittance at the given wavelength (λ_1)

$T(\lambda_2)$ = transmittance for some longer wavelength above noise

K = ratio of $\int_{t_1}^{t_2} \ell nT(\lambda_1)dt / \int_{t_1}^{t_2} \ell nT(\lambda_2)dt$ when the readings for $T(\lambda_1)$ and $T(\lambda_2)$ are both above noise

As an example, in this manner, the transmittance of light in the visible range was readily calculated despite millionfold attenuation of light by the clouds.

For a two-component system, e.g., smoke and dust, equation (13) becomes

$$\ell nT(\lambda_1) = K_1 \{\ell nT(\lambda_3) - K_2 \ell nT(\lambda_2)\} + K_3 \ell nT(\lambda_2) \tag{14}$$

Here two wavelengths are used to predict the transmittance in the visible range. The K values are determined using

$$K_1 = \left(\frac{\alpha_S(\lambda_1)}{\alpha_S(\lambda_2)} - \frac{\alpha_D(\lambda_1)}{\alpha_D(\lambda_2)}\right) \Big/ \left(\frac{\alpha_S(\lambda_3)}{\alpha_S(\lambda_2)} - \frac{\alpha_D(\lambda_3)}{\alpha_D(\lambda_2)}\right)$$

$$K_2 = \alpha_S(\lambda_3)/\alpha_S(\lambda_2)$$

$$K_3 = \alpha_S(\lambda_1)/\alpha_S(\lambda_2)$$

In this case K_1, K_2 and K_3 were determined using transmittance values $T(\lambda_1)$, $T(\lambda_2)$, $T(\lambda_3)$ above noise, $\alpha_S(\lambda_X)$ and $\alpha_D(\lambda_Y)$ are extinction coefficients for smoke and dust at wavelength λ_X.

Extinction Coefficient (α). The extinction coefficient for a specified wavelength can be calculated from field data, using the transmittance and chemical impinger data. The theory for this calculation is developed by starting with the Beer-Lambert law.

The attenuation of a plane wave is given by the Beer-Lambert law as follows:

$$I = I_o e^{-\alpha c x} \tag{15}$$

where I/I_o = transmittance (T)

I = transmitted intensity

I_o = incident intensity

α = extinction coefficient (m^2/g)

c = concentration of droplets (g/m^3)

x = pathlength (m)

The differential form of Eq. (15) is: $\frac{dI}{I} = -\alpha c dx$ (16)

Multiplying both sides of Eq. (16) by (dt) so that $\frac{dI}{I}dt = -\alpha c dx dt$ (17)

and integrating yields $\int_{t_o}^{t_f} \int_{I_o}^{I} \frac{dI}{I} dt = -\alpha \int_{x_o}^{x_f} \int_{t_o}^{t_f} c\,dt\,dx$ (18)

The dosage (D), obtainable from chemical impinger data, is given by

$$D = \int_{t_o}^{t_f} c\,dt \qquad \text{(see Figure 7)} \tag{19}$$

Eq. (19) now becomes $$\int_{t_o}^{t_f} \ln(I/I_o)dt = -\alpha \int_{x_o}^{x_f} D\,dx \tag{20}$$

The extinction coefficient can then be determined from Eq. (20) in the form

$$\alpha = -\int_{t_o}^{t_f} \ln T\,dt \Big/ \int_{x_o}^{x_f} D\,dx \qquad \text{(see Figure 8)} \tag{21}$$

Extinction coefficients for unconfined clouds of phosphorus and HC smokes, and for dust, have been successfully obtained by this means.

Submunition Source Parameters. In general when a smoke munition is constructed using submunitions the computer model concept is to utilize parameters defined for the submunition and build up to the full munition. Proper modeling requires knowledge of certain input parameters such as submunition yield fraction, burn rate and cloud geometry. The submunition yield fraction (MYF) was determined in the wind tunnel using MYF = M_x/M_o (22) where M_x is the total mass in grams of P or Zn that passes through the sampling grid in the wind tunnel and M_o is the mass in grams of the submunition.

The amount of aerosol $M_x(t)$ in the air at any time was determined using a load cell to measure the mass loss of the submunition as a function of time and is given by

$$M_x(t) = M_o \cdot MYF \cdot (M_o - M_s(t))/(M_o - M_s(t_b)) \tag{23}$$

where $M_s(t)$ = mass of the submunition as a given time t

$M_s(t_b)$ = mass of the submunition at the burn-out time, t_b

$M_x(t)$ was reduced to

$$M_x(t) = M_o \cdot MYF \cdot \{A + B(t/t_b) + C(t/t_b)^2 + D(t/t_b)^3\} \tag{24}$$

where the coefficient A, B, C and D were determined from experimental burn rate test data. (See Figure 9)

The initial cloud dimensions were determined using photographic methods. Three motion picture cameras (35mm) were used to record the height, width and length of the cloud before the wind disturbed the initial cloud geometry.

DISCUSSION: The mathematical procedures and associated instruments have been found to be powerful tools for characterizing obscuring clouds. Efforts are now in progress to extend the type and applicability of instruments and grids to accommodate tests with obscurants other than conventional smokes, to permit dynamic testing, and to place further emphasis on use of remote sensing devices. Although a small number of chemical impingers has been employed during recent tests, these have principally served as back-up samplers and for calculation of extinction coefficients. In circumstances for which field-validated extinction coefficients are now available (or not needed), and where back-up samplers are not necessary, the impingers are superfluous.

Instrumentation and methodology have permitted collection of a wide range of data essential to evaluation and characterization of smoke, smoke munitions, dust, electro-optical systems and human perception of targets, and have resulted in input data vital to mathematical modeling of obscuration. Among the parameters successfully investigated were:

1. Complete set of munition data, such as hardware evaluation, ballistics performance and similitude, submunition burn time, burn rate and efficiency, and photographic data such as initial cloud dimensions.

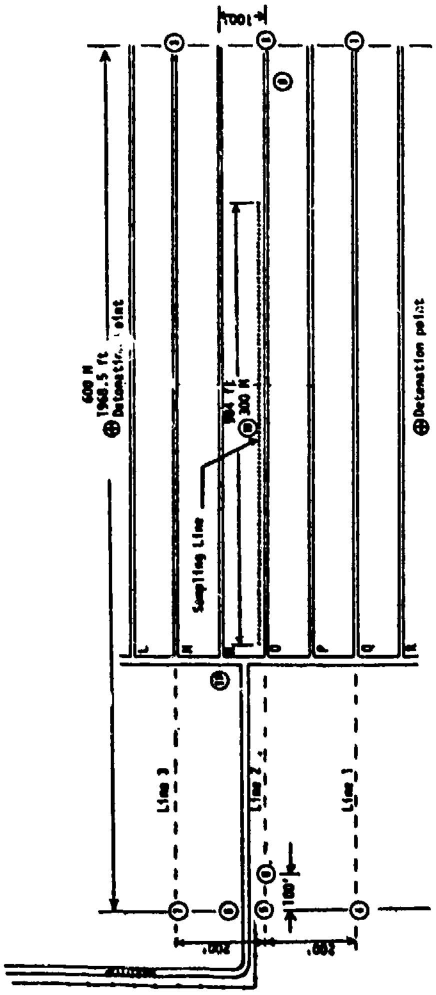
2. Optical data, including transmittance of cloud and atmosphere at various wave lengths without resorting to eye-hazardous sources of radiation, luminance of background, targets, smoke clouds and atmosphere.

3. Physical aerosol characteristics including particle size distribution, number density, mass concentration dosages, and extinction coefficients of unconfined clouds.

4. Meteorological and target area data in the great detail necessary for mathematical modeling of cloud behavior and obscuration, and for test design and control.

SUMMARY: In the course of approximately one year following tasking by the Test and Evaluation Command in 1976, a complete capability for field testing and evaluation of obscuring smokes and munitions and, to a more limited extent, for dust was established. The rugged, reliable, automated system which met a critical need, was employed in full-scale testing during 1977, where it served in one case during 62 essentially consecutive trials without failures or downtime. In these, the first objective field characterizations of a series of inventory and foreign smoke munitions, the new methodologies, grid and associated instrumentation functioned as designed, yielding novel and important information on the performance of munitions and the obscuring properties and characteristics of smokes and dust. Additional field tests are projected. An on-going program of improvement of instruments and methodology will ensure responsiveness to new testing requirements, as well as continued reliability and economy of operations.

FIGURE 1. A TYPICAL BIDIRECTIONAL GRID ARRANGEMENT FOR STATICALLY-FIRED MUNITIONS, WHERE THE NUMBERS HAVE THE FOLLOWING SIGNIFICANCE:



(1), (3) 3.4 μm pulsed sources

(2) 8-12, 3.4, 1.06 and 0.4-0.7 pulsed sources; black, white and OD targets

(4) (7) 3.4 μm receivers

(5) two 0.4-0.7 μm (photopically-corrected) receivers; two 1.06 μm receivers

(6) 3.4 and 8-12 μm receivers

(8) black and white targets (90° each on rotating disk, 180° open for measurements of black target at (2))

(9) 32-meter meteorological tower, with 1.06 μm elevated slant-range transmissometer source

(10) 300-meter sampling line with 100 chemical impingers, 15 aerosol photometers, and 3 particle-size analyzers and 15 total-dose dust samplers

(11) 1.06 μm slant range receiver at 5-foot level

Not shown because of the scale are location of photographic instruments.

For dynamic firings, a longer line of sight could be required.

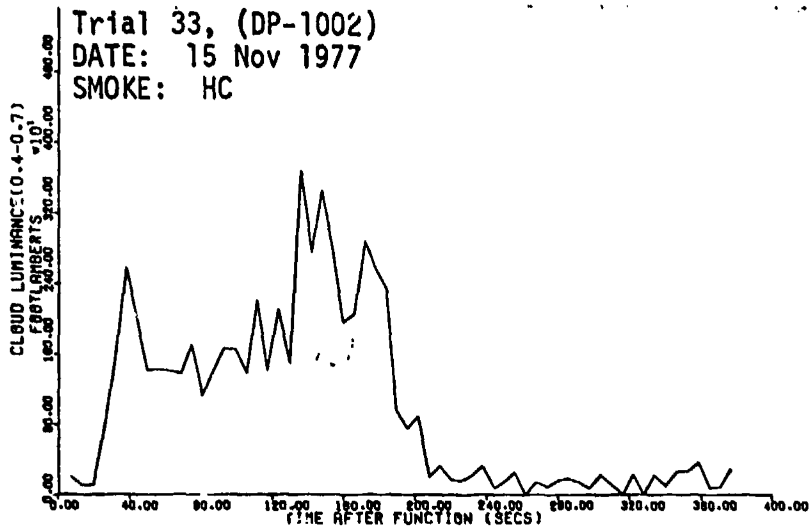


Figure 2. CLOUD LUMINANCE VS TIME FOR WAVE LENGTH BETWEEN 0.4 AND 0.7 MICRONS MEASURED ALONG ROW 0 (Line 2)

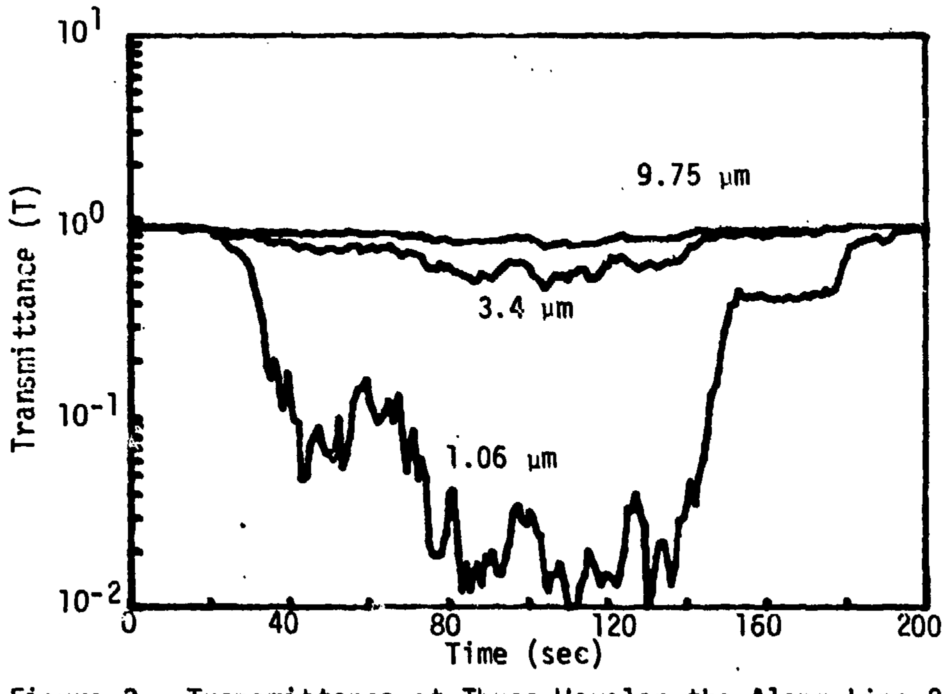


Figure 3. Transmittance at Three Wavelengths Along Line 2, Trial 33 (DP-1002, 15 Nov 77, HC)

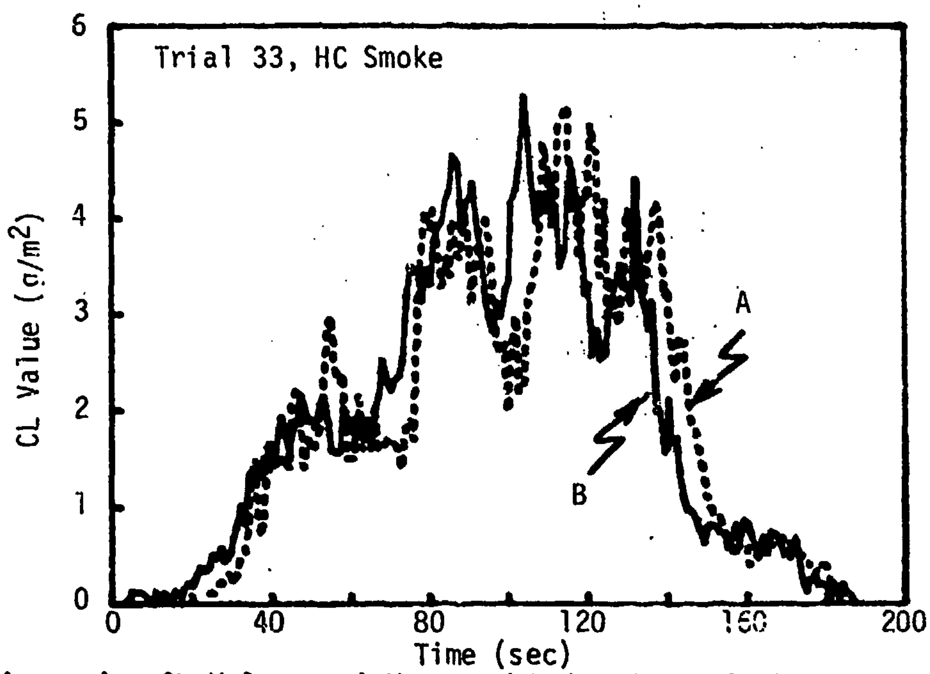


Figure 4. CL Values: A-Measured Using Aerosol Photometers (Eq. 8) B-Calculated from Transmittance at 3.4 μm (Eq. 9). Note time shift due to distance between lines of sight and good agreement of data.

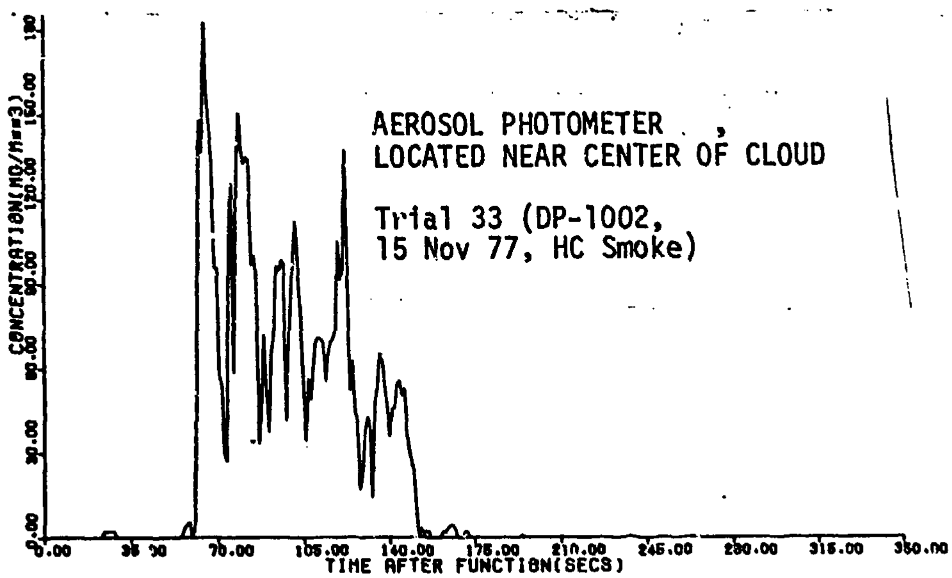


Figure 5. Typical Measured Smoke Concentration Data, Using Aerosol Photometer

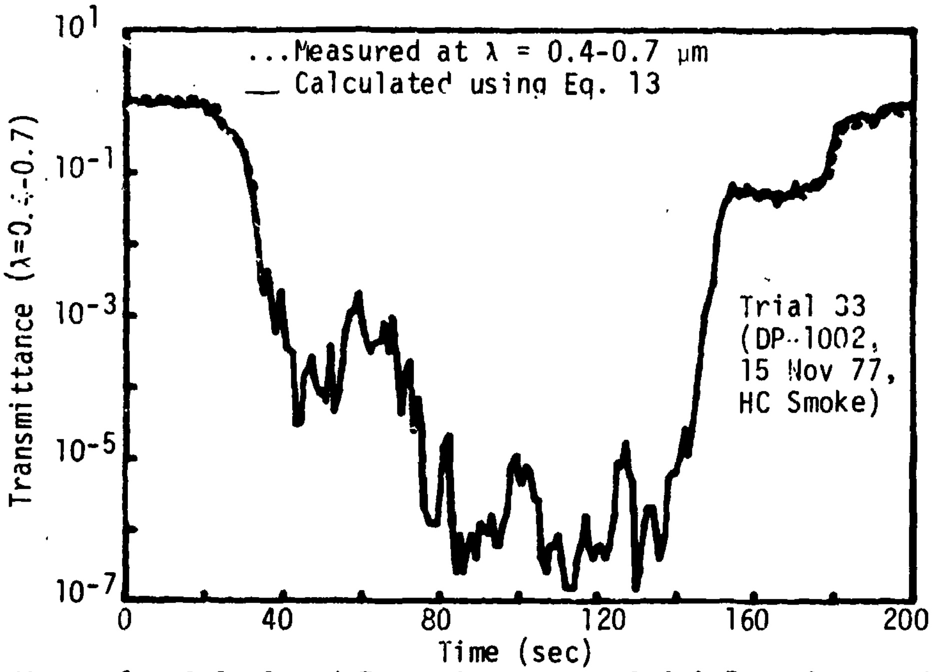


Figure 6. Calculated Transmittance at 0.4-0.7 μm Compared to Measured Values. Excellent agreement is noted down to lower limits (T=.05) of measurements in visible range.

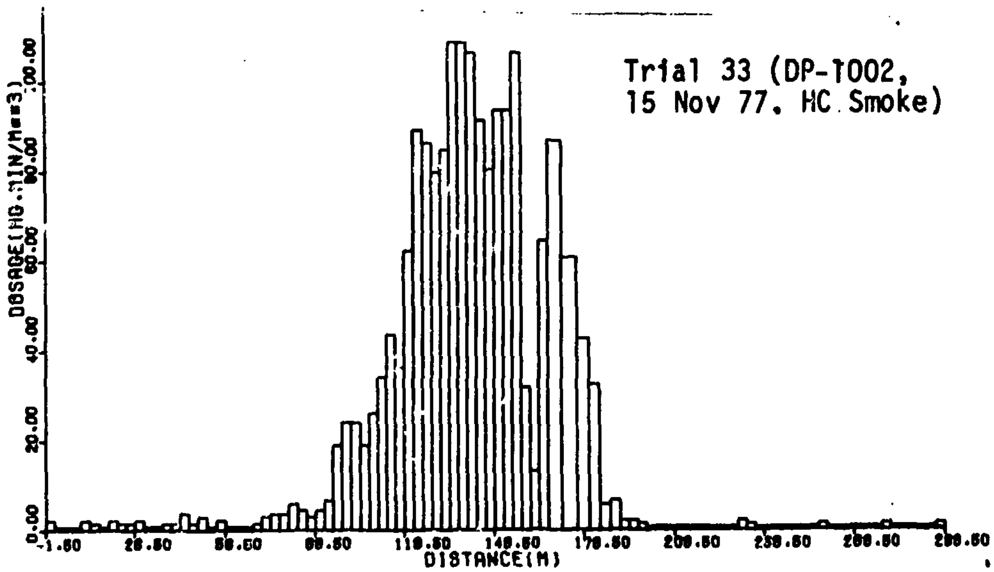


Figure 7. Dosage vs. Distance Along Line 2.

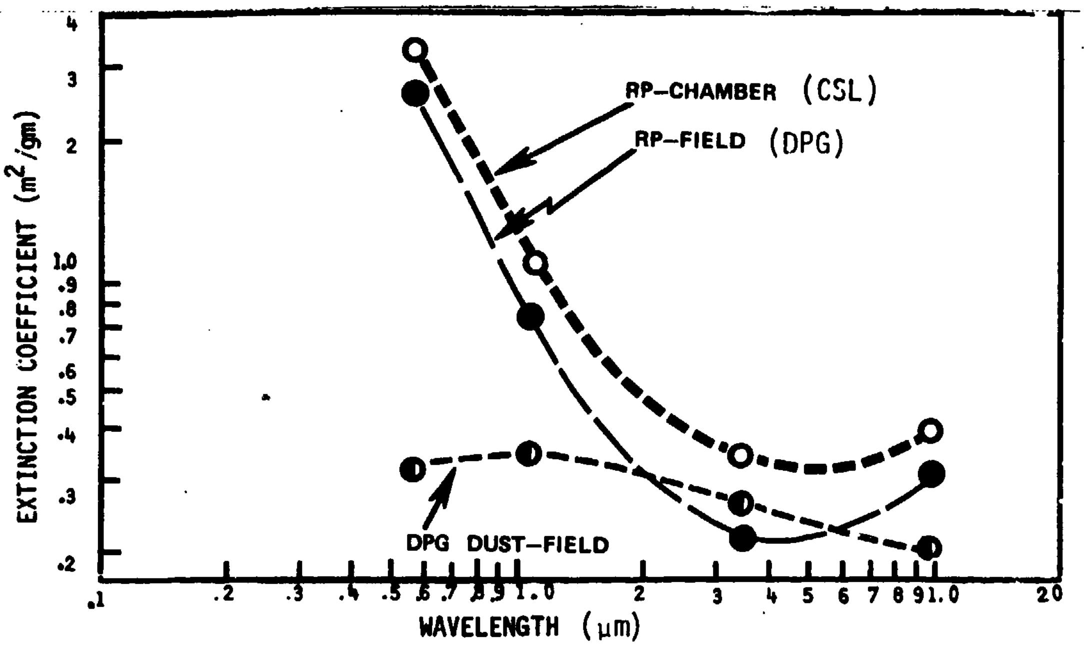


Figure 8. EXAMPLE OF EXTINCTION COEFFICIENTS (m^2/g) DETERMINED FROM EIGHT FIELD TRIALS. VALUES FOR RED PHOSPHORUS (RP) ARE COMPARED WITH CSL CHAMBER DATA.

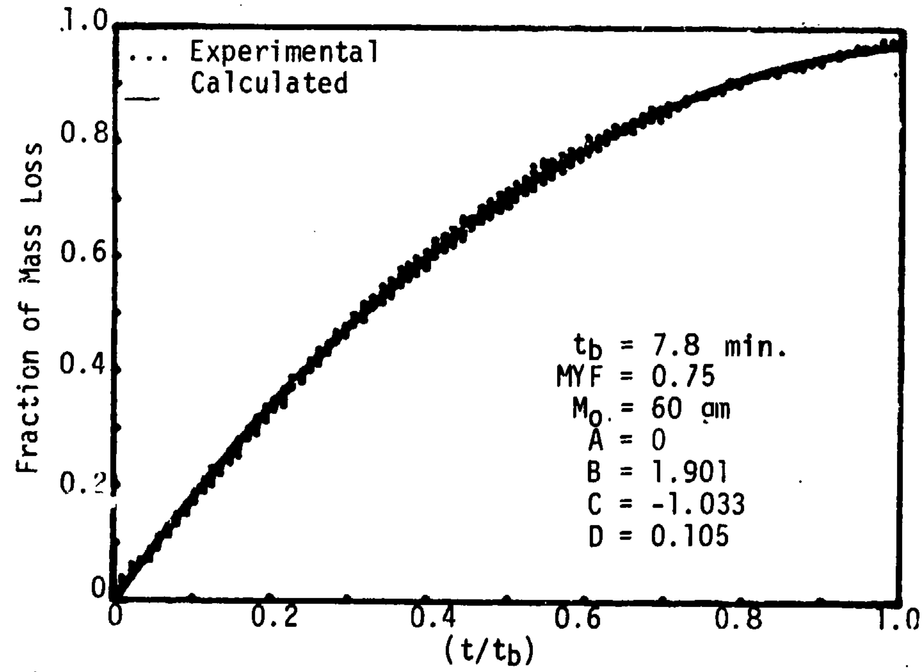


Figure 9. Submunition Source Parameters of Three-Inch WP Wick

Table 1. Typical Test Data from Trial DPI-002-T-33, 15 November 1977, 1201 MST (HC Smoke, 105 mm M116E2, 6 projectiles)

Wind Direction (Transport) (degrees) (4m)	160
Mean Wind Speed (Transport) ($\bar{u}$, m/sec)	2.3
Std. Dev. in Azimuth Wind Angle (σ_a, degrees) (8m)	18.5
Std. Dev. in Elevation Wind Angle (σ_e, degrees) (8m)	7.3
Temperature Gradient, 0.5-8m (ΔT, ^oC)	-1.7
Power-Law Exponent of Vertical Profile of Mean Wind Speed (P) (2m-8m)	0.08
Pasquill Stability Category	C
Relative Humidity (percent) (2m)	26.5
Solar Azimuth (deg)	175.5
Solar Altitude (deg)	31.1
Air Density - ρ(kg m^{-3})	1.055
Solar Radiation (Langleys)	0.88
Barometric Pressure (millibars)	872
Visibility (km)	137
Reflectivity, OD Target	0.11
Haze (footlamberts)	159
Brightness, Background (footlamberts)	1330
Brightness, White Target (footlamberts)	1359
Number of Munitions/Submunitions Used	18
Number of Munitions/Submunitions Functioned	18
Particle Size Range (μm) (0.3-0.4) Fraction -	0.19
(0.4-0.6)	0.22
(0.6-0.8)	0.20
(0.8-1.0)	0.16
(1.0-1.5)	0.16
(1.5-3.0)	0.06
$Log_{10}NMD$	-0.178
$\sigma Log_{10}NMD$	0.232
NMD	0.66
MMD	1.44

Initial Cloud Dimensions (Meters)

Time	Length	Width	Height
1201:00	4	50	3
1201:30	68	69	11
1202:00	113	59	30
1202:30	154	60	27
1203:00	222	81	36